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A PLAN FOR COMPARING THE TRIANGULATED IRREGULAR NETWORKS (TIN) --ETC(U)
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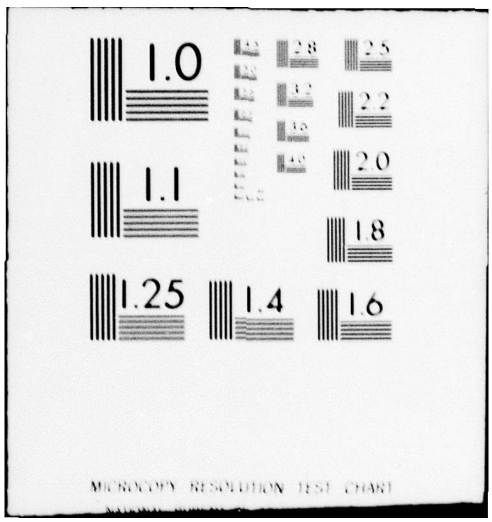
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Naval Warfare Research Center
Research Memorandum

July 1978

A PLAN FOR COMPARING THE TRIANGULATED IRREGULAR NETWORKS (TIN) AND UNIFORM RECTANGULAR GRID (URG) METHODS OF DIGITAL TERRAIN MODELING

By: WILLIAM H. FRYE

Prepared for:

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SRI Project 6726

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INTRODUCTION

Digital terrain modeling (DTM) is concerned with the digital storage, analysis, and display of surface configuration data (x,y,z) for topographic mapping. The field of DTM is relatively new and growing. Many methods of DTM have been studied and applied to real problems, but two are of concern here: the uniform rectangular grid (URG) and the triangulated irregular network (TIN) methods. This technical note presents preliminary evaluation methodology that will be used to compare the TIN and URG methods in the specific context of Marine Corps ground combat operations.

In applications, the URG is by far the most widely used method. Other names used for this method are regular grid, regular rectangular grid, elevation map, or simply grid. The concept is quite simple: store elevation data at uniformly spaced intervals in a rectangular coordinate system, and use interpolation at all other points.

The TIN methodology is a triangle-based system of DTM. The TIN method has been developed over the past several years by a group at Simon Fraser University (SFU) at Burnaby, British Columbia, under the leadership of Professor Thomas K. Peucker. The Geography Programs office of the Office of Naval Research has sponsored much of the research.

The TIN concept is more difficult to describe succinctly than the URG concept. Basically, a portion of the earth's surface is approximated by a collection of connected triangles in (x,y,z) space whose vertices are chosen to minimize the total number of points required. Usually the points will be chosen in an irregular manner, and many will be points of high information content (such as mountaintops, streambeds, ridgelines). Such points are called surface-specific points, and the TIN is considered a surface-specific method.

It is not difficult to convince oneself that a given accuracy can be achieved with fewer points using the unconstrained point selection of TIN

than with the constrained points of the URG method. The number of elevation points to be stored is only one of many things to be considered, however.

The many steps involved in computer storage and processing and the pre-processing time and cost required to get the data into the computer in the appropriate format to begin with are complicating factors that must be considered in the evaluation methodology. Thus a major part of the evaluation problem concerns measuring computer resources required for the two methods of DTM.

A second major aspect of evaluation methodology has to do with applications. The question is, "Given that the methods have somehow been computerized, how well do they perform?" This question has been discussed in general for many years by workers in cartography, topographic mapping, geology, geodesy, and other fields concerned with representing and describing the earth's surface. This is no apparent general agreement concerning evaluation--a specific context seems to be required, and usually this is not available or is too narrowly defined.

The present study differs from most others requiring comparative evaluation of different DTM methods in that a specific application area, Marine Corps ground combat operations, has been selected for the evaluation. In many respects this narrowing makes the determination of performance measures easier for the evaluation than it is for the general problem, at least when measures are considered one at a time. It does not necessarily make the selection of a composite measure any easier, however. This report considers measures individually and does not address the need for, or construction of, composite measures.

DISCUSSION

The Evaluation Concept

The first and most important step in the comparative evaluation of the TIN and URG methods will be a comparison of computer resource requirements and performance measures for a suitably selected set of test problems on representative terrain in the context of Marine Corps ground operations. This document focuses largely on definitions of computer resources, performance measures, and test problems; selection of a baseline for making comparison; and methods for achieving comparability. The terrain test area will be a region near Twenty-Nine Palms, California, that fortunately provides the required variety of terrain types needed for evaluation.

The baseline representing the "true" terrain against which both the TIN and URG methods will be compared will itself be a uniform rectangular grid with spacing that is closer than is actually needed in the test problems. The surface-specific points for the TIN will be selected from these closely-spaced grid points. The URG that is to be evaluated will consist of a subset of points from the baseline grid, and interpolation will be required at all other points. For example, a URG to be tested may have a grid size twice that of the baseline so that it contains every other point in both the x and y directions. The remaining points can be thought of as "held back" for evaluation purposes. Further explanation of this baseline concept, which is central to the entire evaluation, is given in a separate section.

Test Problem Areas

Test problems from Marine Corps ground combat operations that have been selected for the evaluation are in the areas of air defense, fire support, accessibility, and helicopter operations. In air defense, the main relevant considerations, for either selection of a radar site location

or estimation of detectability of low-flying aircraft for a given site, are radar masking and clutter. Radar masking and clutter are two-dimensional (area) problems.

Fire support problems involve both observation and weapon trajectory considerations. For observation, a DTM should be able to predict whether an observer at A can see a target at B and relay the target information to weapon firing point C. Trajectories prediction is also required to see whether a weapon of a given type (ballistic) can reach the target or whether the terrain masks the target. Each of these fire support problems is one-dimensional; the DTMs must estimate a profile along the line of bearing from one point to another.

Certain accessibility or mobility questions are of this sort: "Can a vehicle of a given type (truck or tank) get from point A to point B?" i.e., "Is point B accessible from point A?" This is another one-dimensional problem for the DTM, a "trial" path (in x, y coordinates) will be specified and the profile along this path calculated from the DTMs. The accessibility question will be answered from analysis of the profile.

A final class of problem considered has its origin in the need for finding safety corridors for helicopters during vulnerable periods of flight. This problem, with its required algorithms and appropriate measures, is less well understood than the others and thus requires more development. It surely involves line of site (LOS) considerations, and it may also require a one-dimensional trial path, as did the accessibility problem.

Measures for Evaluation

Measures to be used for evaluation are of two kinds: measures of computer resource requirements and measures of performance. For a given computer system installation, a computer resource measure may be considered already known: the numerous processing time and storage considerations are weighted and aggregated by the system's pricing algorithm, and the measure is dollars. Our problem is not so simple, however. Our computer resource measures will permit estimation of resources for a variety of systems,

large and small, with different central processor/mass storage configurations. We want measures that are as system-independent as possible and that are not necessarily measured in dollars. The principal components identified are storage requirements for the elevation points, auxiliary data, algorithms needed for processing, storage accesses, and the number of basic computer operations.

Performance measures are necessarily problem-dependent. Problems tend to be either two-dimensional (area) or one-dimensional (usually profile). Area problems tend to have binary qualities--e.g., for a given radar site location and antenna height, any given point is either masked or it is not. Thus one can calculate, for each DTM evaluated, a map showing masked points. This map can be compared with a corresponding map generated for the true (baseline) terrain. Two kinds of differences in the maps will be found; areas that are truly* masked will be occasionally shown as unmasked by the DTM, and parts of the areas that are truly unmasked will be shown as masked. Using terminology from statistics, these differences can be considered type I and type II errors, respectively. Alternatively, from detection theory, the differences correspond to missed detections and to false alarms when the "target" is considered to be a point that is truly masked. Two performance measures can be immediately defined for these situations: measure 1 is the areal measure of the type I area and measure 2 is the areal measure of the type II area. The sum† of these areas, which is simply the area of the region where the DTM method was in error, is a third measure.

Profile or LOS problems may also be considered binary. In intervisibility contexts, such as "Can an observer at A see a target at B?" the answer is a simple "yes" or "no." The answer delivered by either of the DTMs can be correct or incorrect according to the baseline. Binary area problems also involve type I and type II errors: truly* visible targets

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*According to the baseline.

†Type I and type II errors will vary in relative importance from problem to problem. Weighted sums, rather than the simple sum, of the measures will be developed as the study progresses.

can be considered masked and truly masked targets can be considered visible. Due to the arbitrariness of A and B (observer and target locations) the appropriate measures will be defined by averaging over many A, B combinations with a suitable probability distribution of likely observer positions and likely target positions, given the general terrain area. The measures can be interpreted as probabilities that the DTM estimate is in error.

A measure for the accessibility problem can be constructed along the same lines. If a definite specified criterion determines for a given elevation profile whether point B can be reached from point A, then the DTM binary answer can be correct or incorrect according to the baseline. Errors of types I and II are again possible: accessible points can be called inaccessible, and conversely. (A possible criterion for making the accessible/inaccessible determination involves maximum slope along the profile: if all slopes are less than a specified vehicle-dependent constant the point is considered accessible, otherwise it is not.) It will again be necessary to specify many points A and B and probability distributions over them based on the problem. Fire support measures are similar. Our calculations will involve firing points A, target points B, the terrain between A and B, and a ballistic trajectory that is weapon-dependent. For DTM evaluation, it is sufficient to assume a simplified trajectory, such as a parabola. What one wants to know in a given tactical context is the answer to a binary question, "Can point B be impacted from point A with weapon type C?" Accordingly, a measure is constructed based on the probability of the DTM method giving an erroneous answer. Probability distributions over representative firing points and target points in the test area terrain are again needed.

A summary table can be made of the computer resource requirements and performance measures in the defined ground combat problem areas. Table 1 shows a sample format for such a table for one specified terrain area. The "RM" designators indicate computer resource measures, and the "PM" designators indicate performance measures.

Table 1

MEASURE TABLE FORMAT

Problem Area/Tactical Variable	Computer Resource Measures			Performance Measures	
	Storage (bytes) RM1	Storage Accesses RM2	Basic Computer Operations RM3	PM1	PM2
1. Air defense • Masking map • Clutter map					
2. Accessibility (capability of moving from A to B with vehicle C)					
3. Fire support map • Intervisibility • Weapon trajectory					
4. Helo safety corridor					

Terrain Representation

A basic consideration in the evaluation is, "What criteria should be used for fitting a DTM to the test-area terrain?" For a TIN, ideally one would like to know first the accuracy requirements of the ground combat problem; these would be found by analyzing the tactical situation and determining what is required of a DTM for that situation. Knowing the accuracy requirements, one would then introduce them into the specific point-selection and triangulation algorithms that fit the TIN.

In the evaluation, we must approximate this idealized approach because accuracy requirements are difficult to determine and the "controls" available to fit a TIN are uncertain.

Other concerns about the TIN fitting also bear on evaluation philosophy. Available fitting methods are partly heuristic, and even the automated parts do not have parameters that permit precise control of fitting

errors. Moreover, the accomplishment of a single TIN fitting is expected to be a significant task,* and there will be little time for trial and error methods to improve an unsatisfactory fit.

Therefore, we have designed the evaluation so that it is not critically dependent on how well the TIN fitting is accomplished. Having approximated the ideal fitting approach as well as possible, we will accept the resultant TIN as a black box; we will simply use it in test problems and accept whatever fidelity it may have to the real surface. The fidelity will show up in the outputs (such as radar masking maps) when they are compared with corresponding outputs from the baseline.

For the URG, the surface-fitting situation is different. In one sense, the URG method is considerably more flexible than the TIN method because several different methods for defining a URG from the dense grid baseline may be considered. One may, for example, choose every other baseline point or every third point to define a new URG. An entire family of URGs can be defined from the single baseline URG; the members each having a different grid spacing. We can also interpolate between grid sizes, so that the URG family can be considered a continuum. This continuum is needed in our evaluation approach to achieve comparability of DTM methods.

Comparability of DTM Methods

Several available measures characterize the important aspects of the problem, but they are essentially independent of each other and therefore irreducible in number. When corresponding measures agree for one aspect of the problem, they usually disagree everywhere else. A reduction in dimension is needed.

Assuming that there are only two measures, one for computer resources and one for performance, the problem becomes: "How can one of these measures be eliminated?" The answer is: vary the URG spacing continuously

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*However, discussions with the TIN development team indicate that it may be possible (and desirable) to fit more than one TIN.

until the values of one measure agree exactly. The remaining measure should directly reflect the performance of the DTM methods for the given test problem, since everything else has been made comparable.

Limitations of Evaluation Approach

Our evaluation approach has several limitations. First, the number of terrain types and the number of test problems will be small. For each given terrain/test problem, only a few military problems (tactical variables) can be considered, and their measures will be limited in number. These limitations are inherent in any problem for which no "global" theory is available. One can only choose representative problems as test cases.

A limitation of a different type has to do with military needs in the particular ground combat context. It is likely that a highly precise terrain representation is not required in some problems. Sometimes a "caricature," somewhat analogous to a tourist map, is adequate. In those instances, our evaluation methodology may be biased against one DTM method because the methodology has no explicit parameters relating to problem accuracy requirements. It is fairly clear that TIN, whose basis is irregular points, should be better to represent a caricature of the terrain. The evaluation approach may therefore be somewhat biased against TIN.

The baseline concept involves two assumptions: (1) the dense grid data are error free, and (2) some points are withheld from the methods so that evaluation can be made on these points. The "point-withholding" assumption does not appear to be limiting. The "error-free" assumption is not thought to be critical because we are concerned with a relative problem (TIN vs URG) and not an absolute problem. Sample calculations show that errors in the elevations of the baseline grid will tend to influence TIN and URG equally; their consequences will, therefore, tend to cancel out when comparisons are made. That is, the performance measures would be only slightly changed if the true elevation values were available.*

*This assertion can be tested later in the project by sensitivity analysis. The baseline terrain elevations can be altered slightly (randomly or systematically) by pseudo-errors with magnitudes similar to those of the errors in the baseline. Measures can then be calculated for the perturbed baseline and compared to the baseline.

TEST PROBLEMS FOR EVALUATION

The TIN and URG methods will be evaluated by examining their resource requirements and performance in representative ground combat operation problems of the Marine Corps. Several problem areas have been defined and analyzed to determine whether they need topographic information and what they require of a digital terrain mapping system. For now, the problem areas are being considered individually; such matters as weighting the problems by their relative importance will be taken up later.

The criteria for selection of test problems may be stated informally:

- The test problems should be important to the Marine Corps in ground combat operations.
- The tactical variables (such as LOS) required by the test problems should collectively exhaust the tactical variables required for all DTM problems. We can say that although the test problems are only representative, the tactical variables and the algorithms they require should be fairly complete.
- Test problems should evoke questions that have quantitative answers that are realistic to consider. A sample test problem we would not include is one in which a map-reader must look at the surrounding terrain and determine his location from a DTM-generated map. A complex pattern recognition process would be required for this task and would lead us far afield from this study.
- There should be just enough test problems to touch on all representative areas. Too few test problems would result in an indeterminate evaluation, and too many would result in confusion.
- A variety of terrain types should be called for by the problem.

Problem areas that will be considered are air defense, fire support, accessibility by ground vehicles, and helicopter safety corridor areas. All of these except helicopter safety corridors are discussed in the following sections.

Air Defense

In past in-depth studies at SRI, the dual problems of air defense and aircraft survivability considered LOS the principal tactical variable. Some of these studies have been reviewed for applicability. LOS entered these problems in the form of "the distribution of defense/offense intervisibility segments" found by analysis of aircraft characteristics and tactics and interaction with the defense weapons. As the nature of the LOS became understood, the defensive system characteristics were introduced and survivability and attrition computed. Results were fed back into the problem to suggest a new radar site or changes in defensive siting doctrine.

Air defense problems will arise in most significant areas of Marine Corps operations. The scope of the present study precludes duplication of methods used in earlier studies; something much simpler must be done in the present study. Since the major considerations in selection of a radar site are masking and clutter, we have decided to base our evaluation on measurements that can be made from radar masking and clutter maps. The simplest maps of this kind represent the (x,y) space surrounding the antenna location as either masked or not masked, clutter returns or no clutter returns.

The performance of URG and TIN in air defense test problems, then, will be based on measurements made from maps with binary indications of masking/no masking, clutter/no clutter. Parameters of these problems are (1) site location (x,y), and (2) antenna height (z). They will be determined in the terrain test areas by separate analysis and/or consultation with the Marine Corps, and they will be kept fixed for the performance evaluations.

Fire Support Coverage

Several terrain-related map problems arise in fire support questions, planning, and analysis. Essentially they involve LOS (for observation) and trajectory (for weapon firing) considerations. Due to the extreme variety of fire support problems, only representative situations and

tactical variables can be examined. There are two fundamental kinds of map problems involved: fire support coverage problems and observer-to-target LOS problems.

- For a hypothesized weapon and location in the terrain test area, a map showing points that are covered from the weapon location can be calculated and displayed. In most situations only certain potential target areas will be of interest, so the performance will be tested for only a subset of the terrain.
- In a typical problem we may have three positions involved: an observer is at A, a target is at B, and a weapon that may be able to hit the target is at C. One subproblem is, "Can the observer at A see the target at B?" Another subproblem is, "Can the weapon whose ballistic trajectory possibilities are known fire from C to hit A?" These subproblems can be examined somewhat independently. Both require terrain representations; the better the DTM fits the surface, the better it should answer these questions.

For the observer-to-target LOS problem, a pair of positions are required. They should be where observers might be located. In general, we can't expect to find unique pairs of points for observer and target; therefore, a number of pairs should be selected.

For this evaluation it is sufficient to deal separately with observer points A and target points B instead of (A,B) pairs. Specifically, we will determine (through analysis and consultation with Marine Corps personnel) likely areas for observers and for targets in the terrain test area. Over each of these areas, a probability distribution that represents a weighting of the likelihood of the points being chosen in particular situations will be assumed. Weapon considerations will, to some extent, influence the selection of these areas. It may be necessary to differentiate between types of weapons (by high or flat trajectory weapons, i.e., guns or howitzers). Figure 1 shows how the observer and target areas might be specified in the test terrain. A uniform probability distribution might be assumed over the areas shown to complete the test problem specification.

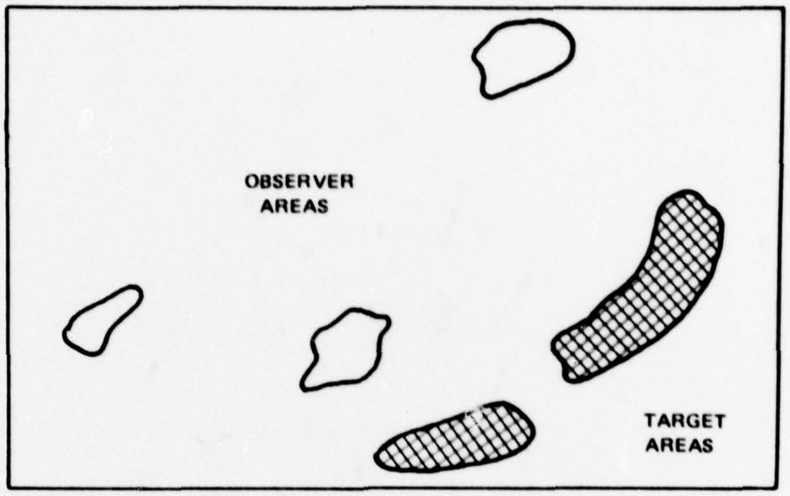

FIGURE 1 OBSERVER AND TARGET AREAS

Accessibility

A common class of Marine Corps problem can be stated generically in terms of a starting point A, a destination point B, and a path joining A and B. For example, point A might be the present location of a portable radar and point B a potential radar site; the path joining them would then be a road over which the radar could be moved to the desired location. Conventional military mapping analysis uses contour maps for drawing a profile along the path to determine accessibility.

In this study, we will develop an algorithm that will automatically draw the desired profile given A, B, and a path of suitable form. Parameters that can be found from the path (such as the steepest downslope) can also be calculated. The approximate path will consist of a series of connected straight line segments. Figures 2 and 3 illustrate elements of the accessibility problem and a display of the profile.

With linear interpolation, the profile for the TIN method will consist of a series of connected straight line segments (Figure 3). The form of the profile display for URG will vary with the interpolation method. One common method arbitrarily divides each rectangle of the grid by arbitrarily choosing one of the diagnals and then fits a linear surface

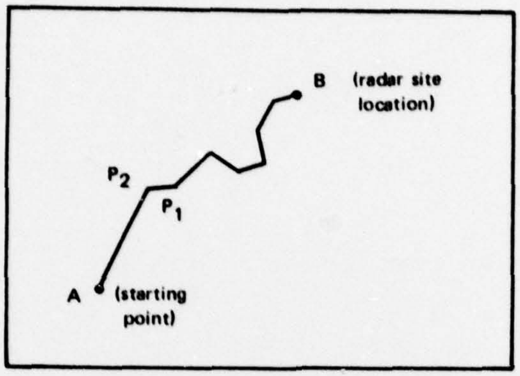

FIGURE 2 PATH SPECIFICATION FOR ACCESSIBILITY PROBLEM

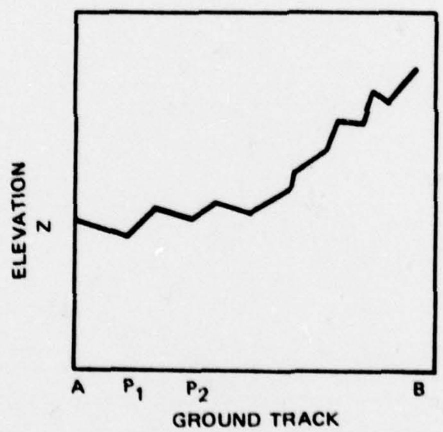

FIGURE 3 PROFILE DISPLAY

triangle over each of the triangles formed. This linear interpolation method will also give profiles like Figure 3. One simple alternative method employs bilinear interpolation of the form $z = z_o + a \times x + b \times y + c \times x \times y$. The profile from this form will consist of curved segments.

DEFINING A BASELINE

Determining an adequate baseline is often difficult for studies involving cartographic surfaces. Aerial photography is sometimes used when suitable photographs are available. For some studies, the discrete elevations over a uniform grid are simply decreed to be the baseline. In other studies, a baseline is dispensed with entirely--two different DTMs are evaluated by first forcing one of the two measures or criteria to equality, then comparing the second measure.

The baseline proposed for this study is derived from the latter two methods. We first assume that the elevations over a particular* dense uniform rectangular grid represent the "true" surface at the grid points. Because the baseline grid has a small spacing, the surface-specific points of the TIN can be constrained to be grid points of the baseline. The TIN selected from the grid points should be very close to the one that would have been selected from a continuous analogue, such as a contour map. This would not necessarily be true for a large grid spacing. Note that this restriction biases the evaluation slightly in favor of the URG method; the amount of the bias will be estimated and compared with the differences in performance later in the study.

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*It should be noted that although the baseline itself is a uniform rectangular grid, we do not refer to it as a URG in this document to avoid confusion with the URG method of DTM that is being evaluated.

MAKING THE TIN AND URG METHODS COMPARABLE

In contrast with the TIN method, which will use a single representation for the entire evaluation, several URGs will be analyzed. Each URG candidate will be defined as a subset of the baseline grid points by a regular relationship, such as every other point in x and y separately, or every third point. Thus each URG must have specified spacing that will be a multiple of the baseline spacing.

The other important feature in the evaluation is not, strictly speaking, a feature of the baseline. In approximating the earth's surface in the terrain test area, we will only allow the URG to have points that are a subset of the baseline points. (This is in contrast to the TIN, which has access to all the baseline points.) The URG is then forced to interpolate over the remaining points, just as the TIN interpolates. (Linear interpolation will be employed for both DTMs.) The outputs that the URG generates will depend on the points it had access to and the interpolation method. The same is true for the TIN, which had access to all of the points.

One might question whether this method introduces a bias toward one of the DTMs. We feel that it does not. TIN can only employ a continuous map for its point selection, but since the baseline grid is dense, each surface-specific point selected from the continuous map will have a grid point in the baseline not far away. Thus, the TIN approximation will be very close. The essential point to note is that the TIN can choose as many points as it likes to triangulate and fit the surface, but it must incur the penalties in computer resources. The situation is similar for the URG: finer grids should give better outputs but use more computer resources.

The evaluation concept can be clarified by describing a hypothetical situation in which there are two contenders--one advocating TIN, the other advocating URG--and an unbiased evaluator. The evaluator has determined

the terrain test area, the ground combat problems to be considered, and the kinds of tactical variables and the maps or other displays that are needed in these problems. Moreover, the measures of computer resources and performance are both defined by the evaluator. All this information is given to both the TIN contender and the URG contender so that they can design their best products to be submitted for testing and evaluation.* They are both given the baseline grid as well. Other relevant considerations, such as relative weighting of the different ground combat problems or tactical variables, may be ignored for this exposition.

Is this information sufficient for the contenders? Shouldn't they know how good the fit to the surface must be? The answer is: not according to the evaluation method given here. Performance measures are computed by comparing the contender's respective outputs with the baseline's outputs; none of this depends on how well the approximate surface has to fit the actual surface. Improved fits will always result in improved measures, but the improvement may not have practical significance.

The TIN contender is guided in his search for surface-specific points by knowledge of the evaluation; he knows that the more points he chooses the more penalties there will be for computer resources. In principle, the selection of points could be made into an optimization problem and be purely mechanical. A family of TIN solutions could be found: for each hypothetical amount of computer resources, one would choose points that optimize the performance measures. But which member of the hypothetical family of TIN approximations, all of them optimized, should be selected? The answer, in general, depends on how computer resources measures and performance measures are to be traded off. To make all this precise would be difficult and would involve weighting type I and type II errors and the relative importance of the different tactical problems. Given full and precise statement of the problem, optimization could, in principle, be carried out. A reasonable and realistic rationale for the TIN approximation

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*Actually, the URG contender has nothing to do--there is no choice left to him. The contender viewpoint would be more symmetrical if URG were replaced by some other more complex DTM method.

is that it should only satisfy the accuracy requirements of the ground combat problems to the extent that these requirements can be determined.

The logical possibilities that may be encountered in making the comparisons are shown in Figure 4. Recall that our performance and computer resource measures have been defined so that small values are preferable to large ones. Consider the test problem and terrain as given. For the single TIN approximation, a pair of numerical values, one for each measure, determines a single point (x) in the diagram. Similarly, any one URG determines a single point. By varying the grid spacing and interpolating between them, an entire curve is determined.

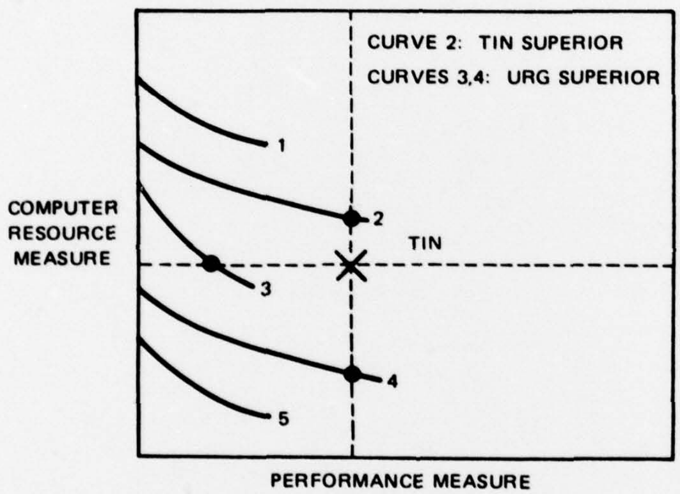

FIGURE 4 AGGREGATED MEASURE PLOT

Figure 4 shows the possible types of curves that may occur. Notice that all URG curves start at the "y" (computer resource measure) axis because performance measures (errors of type I and II) have zero value for the baseline URG. For each of the URG curves, the grid spacing increases from left to right. An increased spacing should degrade (increase) the performance measure and simultaneously reduce the computer resource requirements. The URG curves therefore have the shape indicated. There are five ways that a curve may be traced out in the aggregated performance measure plot. In cases 2, 3, 4, and 5, TIN and URG are comparable for one

measure. In case 1, the methods are not comparable: URG performance is always superior to TIN, but it also always requires more resources. Case 1 is considered unlikely since a sufficiently sparse grid should perform more poorly than any reasonable TIN. In case 5, URG always out-performs TIN and always uses fewer computer resources. The URG method is clearly superior here, but this case is also considered unlikely. We therefore expect to be able to make the TIN and URG methods comparable by varying the URG grid size. A curve resembling curve 2, 3, or 4 should be derivable for each problem.

FURTHER DISCUSSION OF MEASURES

This document is concerned with objective means of evaluating the TIN and URG methods. Quantitative measures of two types are required for this purpose: computer resource requirements and performance measures. We regard the two DTMs as "black boxes" with unknown internal structure. By some means or other the parameters of the DTMs have been selected so that the computed elevations are approximately the same as those of the actual earth's surface in the terrain test area. Each method is capable of giving an output, usually a map or a section, in each test problem, and measures will be determined by (1) recording and/or computing suitable quantities to reflect the computer resources required for the test problem, and (2) calculating measures based on the differences between the generated output and the corresponding output for the baseline. Put simply, the computer resource measure tells what it takes to generate the output, and the performance measure tells how closely the output matches the baseline's output according to the needs of the problem. For a given DTM method we would expect these two measures to be related: better outputs should always be achievable (up to a point) with more computer resources. There is no necessary relation between the two measures for two different DTM methods. Therefore, the measures of the two basic evaluation components can be considered separately.

Computer Resource Measures

Measures of computer resources are, in many respects, more straightforward than those of performance. If a commercial computer system configuration were specified as the system on which the TIN and URG methods were to be compared, the resource measure problem would be simple; all storage and processing costs would be aggregated by the system's pricing algorithm, and the resources required would be measured in dollars.

In our evaluation problem, the situation is not that simple. First, no computer system has been specified for the evaluation, and DTM implementation and processing depend on the computer system parameters. It is possible, for example, that one DTM method would outperform the other if a large core memory were available but not otherwise.

Other variables are problem size and the size of the data base are determined by the spectrum of DTM problems to be solved. One DTM method may outperform the other on small problems but not on large ones.

The problem size aspect may be appreciated by analogy with well-known operations research computational problems. Linear programs may serve as an example. Typically, they have a computer running time proportional to the cube of the number of rows in the constraint matrix--a very strong dependence of running time on problem size.

Data base size is another variable that may also result in differing comparisons. Specifically, TIN's access to elevation is expected to become proportionally more difficult than URGs as the data base size increases. It is thus possible that, for a given problem in which TIN and URG performed equally well (according to the performance measures), TIN would require fewer computer resources than URG for a small data base but more computer resources for a large data base.

The computer language employed can also affect the evaluation results. Using the same language for both methods eliminates this effect. Another important programming-related variable is the efficiency of the code. Eliminating this source of variability is difficult in the real world of finite resources. Efficiency considerations come up in several ways and can be subtle. As in any other problem area, one searches for common elements in all problems so that common algorithms can be developed as subroutines for the sake of programmer efficiency. However, for particular problems, it may be worthwhile to develop special-purpose algorithms and codes even though the problems can also be handled by the general-purpose subroutines. A case in point might be the determination of a radar masking map by the TIN method. An intervisibility (LOS) algorithm will certainly be developed that has two <u>points</u> as inputs. This algorithm

may be used repeatedly to generate a radar map point by point, but it may be far better to generate this map triangle by triangle, using some special property of a TIN in this application. This and similar possibilities must be considered individually when programming for the evaluation.

In summary, we have identified the following variables that influence computer resource measures:

- Computer and computer system parameters
- Data base size
- Data base storage medium and its cost
- Computer language for the software
- Efficiency of the code and use of general-purpose subroutines
- Use of general-purpose vs. special-purpose algorithms and subroutines.

Our approach in evaluation is to define measures that are as nearly independent of the computer system as possible. From these basic measures, actual resource requirements in a variety of computer system/storage/language situations can be estimated. Appropriate measures now appear to be:

- Bytes of storage for elevation data and any required auxiliary data
- Number of access to mass storage
- Number of "basic" computer operations.

Each of these will be recorded/determined problem by problem.

The sensitivity of measures to problem size and data base size will be investigated by examining the results from the sample test problems. The test problems will be of varying sizes, so that this dimension of the problem can be probed directly. Data base size will be parametrically varied, perhaps by using dummy data in a large area whose elevations are not needed in the problem.

Performance Measures

The general concept of using performance measures to evaluate the TIN and URG methods has been given earlier: each DTM is regarded as a

black-box that requires certain resources and produces certain outputs in the form of maps or sections. Each output (one output for a defined test problem) will be compared with the corresponding output from the baseline representing the true surface in the test area. Performance measures will be defined in terms of the differences between the DTM-generated approximation and the baseline ("true") map or section.

In general studies of topographic mapping, the goodness of fit of the approximating surface is usually judged by RMS elevation error and/or how well the approximating surface preserves such slopes, roughness, and similar geomorphic parameters. Workers in the topographic mapping community disagree on appropriate measures for evaluating different models. Much of the disagreement arises because the uses to which the map will be put are not known.

Our study assumes applications in the field of Marine Corps ground combat operations only. Because of this specialization, it has been possible to define performance measures in a unified, rather straightforward manner.

A single unifying concept is employed in the definition of most of the performance measures. In effect, we define military ground combat problems that have binary (yes/no) answers. The baseline display needed to determine an answer defines the right answer, and the corresponding display from the approximating DTM can be judged right or wrong by comparing it with the baseline. There are two kinds of errors--"no" when the answer should be "yes" and "yes" when the answer should be "no"--and, borrowing terms from hypothesis testing, one can speak of the probability of errors of type I and type II. These probabilities will be the performance measures with which to evaluate the URG and TIN methods.

Measures for Area Problems

Several of the test problems require calculation and display of an area. For radar masking, the display for a defined target is a "binary map"--each displayed point is shown as either masked or unmasked. The display will consist of a discrete number of points that are a subset of

the baseline. Since the baseline grid has a small spacing, we can think of the display as a continuous map of the form sketched in Figure 5 below. The displayed area is circular with the radar at the center. The radius of the circle is the maximum detection range of the ground radar. Since the threat to the ground forces defense is presumed to be low-flying aircraft, it is necessary to specify the altitude or altitude profile of the target. The simplest such target is adequate for this study; we assume that the aircraft can maintain a given altitude above the ground throughout its flight while within range of the radar. Thus, a single (x,y) point on the display is shown as masked if an aircraft at altitude $z(x,y) + z_p$ is visible to the radar, where $z(x,y)$ is the elevation at (x,y) and z_p is the fixed penetrator altitude above the terrain.

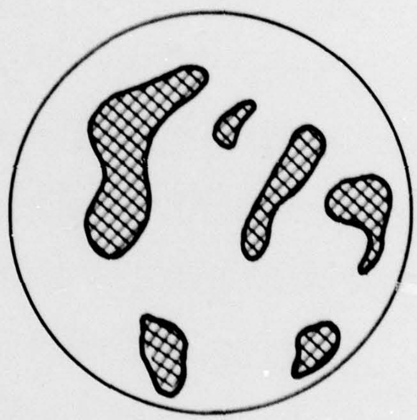

FIGURE 5 DISPLAY OF AREAS MASKED TO THE RADAR

Next, we take either of the DTMs being evaluated (TIN for this illustration), and generate a radar masking map like the one in Figure 5. In Figure 6 we superimpose the two displays so that they may be compared. For convenience, the masked area in Figure 6 is shown as a single area. In general, there will be four areas on the display: (0) an area where neither the baseline nor TIN indicates masking; (1) an area where TIN shows no masking but the baseline shows masking; (2) an area where TIN shows masking but the baseline shows no masking; and (3) an area where

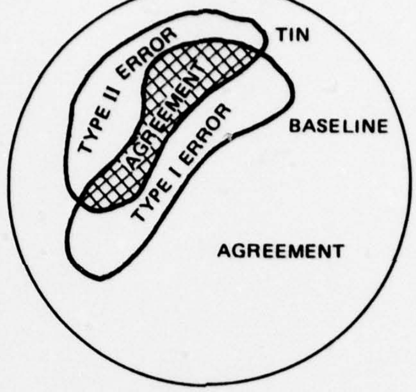

FIGURE 6 COMPARISON OF MASKED AREAS

both methods show masking. The methods agree in areas 0 and 3 and disagree in areas 1 and 2. The disagreements, by definition, are errors of types I and II, respectively, for the TIN method.

Denote by A_i the measures of the four areas $i = 0,1,2,3$ and let A_t be the total area. Then if an (x,y) position is chosen at random from the display, the probability that the masking indication from TIN will be correct is $(A_0 + A_3)/A_t$, and the probability that it is incorrect is $(A_1 + A_2/A_t)$. The probabilities of type I error and type II error are A_1/A_t and A_2/A_t.

STEPS TO IMPLEMENT THE DEMONSTRATION AND COMPARISON PLAN

Several steps are required to implement the TIN-URG comparisons outlined above. These steps are detailed below.

Step I	Obtain TIN source code and documentation from Simon Fraser University (SFU). Confer with SFU analysts to fill in gaps in documentation and assist in transfer of code.
Step II	Translate TIN source code to SAIL language for use at SRI International on KL-10 computer system.
Step III	Prepare TIN evaluation software 1. Develop/adapt algorithms for calculating/processing tactical variables and measures. 2. Code and debug the tactical variable and measure algorithms from Step III-1.
Step IV	Prepare URG evaluation software 1. Put baseline grid (Twenty-Nine Palms area) on the KL-10 computer system. 2. Develop or modify algorithms for performance and resource measure calculations. 3. Code and debug URG algorithms from Step IV-2.
Step V	Select terrain test areas for sample problems.
Step VI	Prepare a "TIN" for the selected test areas using SFU-developed method and software (the software is included in Steps I and II).
Step VII	Run the evaluation software for TIN and URG for tactical variable/test area combinations.
Step VIII	Analyze the results of STEP VII and make plots of the form in Figure 4 to make TIN and URG comparable.
Step IX	Write a short report summarizing the results.
Step X	Demonstrate the comparisons at SRI International.